ROSAT OBSERVATIONS OF LOW MASS DISK GALAXIES: NO EVIDENCE OF BARYONIC BLOW OUT

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Abstract

To test the hypothesis that galactic winds associated with star formation in low mass disk galaxies can be an effective means of relocating cold disk gas to a warm tenuous halo, we have obtained long exposure ROSAT PSPC observations of three such galaxies. The sensitivity of the PSPC to the presence of an extended, approximately 0.1 KEV halo, is quite high for the exposure times we used. We failed to detect this halo in all three cases and the observed X-ray luminosity of the galaxy is two orders of magnitude less than the hypothetical case in which the mass of gas that has been expelled by previous generations of star formation is equal to the stellar mass of the galaxy itself. Thus, we were unable to directly verify the presence of significant galactic winds in these three galaxies either because they are not operative, or because their halos are not sufficiently massive to aid in the retention of this gas. We also report here the serendipitous detection of Abell 1560, a distance class 7 cluster of unknown redshift.

Subject headings: galaxies: X-ray observations galactic winds

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1 introduction

In principle, the galactic mass-loss which is induced via supernovae heating and winds may be the most significant factor in determining the overall chemical evolution/star formation history of galactic disks, In extreme cases, this mass-loss or baryonic blow out (BBO) may be sufficient to drive most of the gas completely out of the galaxy and thus terminate its star formation history. Galaxies which are most susceptible to terminal BBO are those in which the velocity dispersion is low, $\sim$ 100 km s^{-1} (e.g., Dekel and Silk 1986; Silk et al. 1987). The subsequent evolution of such a disk would be to fade rather rapidly and to eventually assume the appearance of a metal-poor, low surface brightness (LSB), low-mass disk. It has been suggested that such fading (see Babul and Rees 1992) can help to explain the apparent excess of faint blue galaxies that turn up in deep CCD searches (e.g., Lilly et al. 1 $]{]]). This faded population is potentially an important repository of baryonic matter in the Universe (Cowie 1989; Colles et al. 1990). However, we hasten to add that a recent exploration of this entire issue by Koo et al. (1993) indicates that the degree of "excess" in the faint blue galaxy is a strong function of the assumed luminosity function of galaxies at z 0. Based on this, Koo et al. (1993) conclude that such dramatic fading may no longer be warranted or required to explain the faint galaxy counts, although this conclusion is likely to remain controversial. Still, the idea of BBO or failed galaxies remains a compelling one since it seems unlikely that galaxy formation was a very efficient process whereby most of the initial gas mass available to build galaxies is actually retained by them.

Strong confirmation of the existence of galactic winds comes from a variety of different observations. Forman, Jones and Tucker (1985) have shown that many luminous elliptical galaxies are surrounded by contours of X-ray emission that substantially exceed the optical size of the galaxy. The most viable explanation for these coronae is that mass-loss gas from normal stellar evolution is heated by Type 1 supernova to escape velocity (Mathews and Lowenstein 1986). This lost gas is subsequently trapped by a dark halo and thus appears today as a diffuse, X-ray emitting plasma (see David, Forman and Jones 1990) which is the process of cooling and falling back into the host elliptical. The mass Of gas in these halos is approximately 1 00/0 Of the stellar mass of the galaxy.

Another source of winds is associated with the energetics of star formation. The so-called "superwinds" seen in some luminous IRAS galaxies (Armus et al. 1990) have an impressive momentum flux and lend credence to the idea that terminal BBO is a real possibility, as substantial amounts Of material are being transported to large distances. Can a similar phenomenon occur in the more common low-mass staforming galaxies (typically LMC type irregulars)? Indeed, it has been suggested that the origin of many QSO absorption lines is associated with gas that has been ejected to large distances by these low-mass actively star forming galaxies. This ejection process would result in a relatively large volume that is filled with low column density gas (see Yanny et, al. 1987; Ikeuchi and Norman 1987; Impey and Bothun 1989).

Terminal 11110 may also be connected with the newly discovered population of Low Surface Brightness (LSB) galaxies. In the last few' years, surveys for LSB galaxies have turned up a large number of enigmatic objects which generally have rather blue disks despite a very low current star formation rate (SFR) (see Schombert et al, 1992; McGaugh and Bothun 1994). To date, most of these objects which have been mapped in 11 1 (see van der Hulst et al. 1993) indicate surface densities which are below the threshold which is commonly thought to be required for star formation to occur (Skillman et al. 1987; Kennicutt 1989). Kinematic heating/feedback to this gas, from a period of more active star formation, is an effective means of lowering the overall column density, thus perhaps suppressing the SFR for long periods Of time. Moreover, detailed studies of the extended HI rotation curves of a few galaxies in this class (Jobin and Carignan 1990) indicate the presence of substantial amounts of dark matter which is most likely distributed in the halo component. By analogy with elliptical galaxies, it is possible that gas which is heated and dispersed by star formation in low mass galaxies is retained in this halo. If enough gas is ejected into such a halo so that disk star formation is suppressed for a long period, then the galaxy would fade, perhaps assuming the appearance of a LSB disk galaxy.

The possible existence of coronae around low mass galaxies could not have been detected with the EINSTEIN X-ray satellite. In the case where the velocity dispersion is 100 km s^{-1}) the virial temperature of hot plasma is an order of magnitude less than the Case for a luminous elliptical. This temperature (0.1 kev) is well outside the energy band to which EINSTEIN was most sensitive. However, the ROSAT satellite is sensitive to emission in this energy band. The imaging capability of the detectors make it feasible to search for the presence of extended, diffuse X-ray emitting gas around low mass disk galaxies thus adding more evidence for the process of galactic winds. In this paper we report our results of long exposure ROSAT PSPC observations of three low mass disk systems that are currently in a quiescent stage of star formation. All distance dependent quantities assume H_o = 100 km s^{-1} Mpc^{-1} and Virgocentric infall of 300 km s^{-1} .

2 Motivation and Choice of Sample

2.1 Where Did All the Cold Gas Go?

There is ample evidence that low-mass galaxies experience episodic star formation (e.g., Hunter and Gallagher 1985). The duty cycles of these episodes is not known although most estimates suggest that vigorous star formation in these systems occurs over only 5 10% of their lifetime (see Thuan 1985). Hence, over the majority of a Hubble time, these galaxies arc quiescent. Any substantial fading of the stellar population between episodes of star formation would lead to a LSB object. II I surveys of hundreds of low' mass disk galaxies, both in active and passive star formation modes, now have been done (e.g., Gordon and Gottesman 1981, Thuan and Martin 1981 Bothun et al. 1989a, Schneider et al. 1992, Salzer et al. 1994), In virtually all cases, the fractional 11 1 mass in these systems is no larger than 30% (for an exception see Staveley-Smith et al. 1990) and the average is 10 20%. This seems paradoxical in light, of the very inefficient star formation histories inferred for these s ystems. M or eover, there is now limited evidence (e.g., McGaugh et al. 1994) that some low mass systems have late formation times and yet we still can't find examples of objects which have > 50% of their dynamical mass in the form of gas either through direct observation of known low mass or LSB disk galaxies or by H I searches (Rao and Briggs 1993). Even the giant II I cloud in Virgo (e.g., Giovanelli and Haynes 1989; Salzer et al. 1991), where one peak in the H 1 distribution lacks an optical counterpart, lies in a dynamical configuration which suggests a normal fractional 11 1 content.

In striking contrast, Downes et al. 1993 claim that some ultraluminous IRAS galaxies do have most of their dynamical mass in the form of gas and, of course, these objects are in some kind of super-starb urst phase with energetic winds and rampant mass loss. In these cases the cold gas content is being rapidly depleted th rough a high star formation rate, heating (by supernova), and mass-loss via galactic winds. The lack of substantial reservoirs of cold gas in the low mass systems surveyed to date then might be explained in a similar manner. That is, the cold gas has either been converted to a warm tenuous gas by the most recent star formation event and/or substantial BBO has occurred, which has driven this gas out to large radii. In either of these scenarios we would expect soft X-ray emission from these galaxies whose luminosity would depend both on the temperature (heating rate, depth of potential) and gas mass.

The expulsion of cold gas from star forming galaxies with low gravitational potential walls may also help to understand the unexpectedly large yield of low redshift absorption lines in the line of site toward 3C273 discovered by HST (Morris et al. 1991; Bahcall et al. 1991). These observations straightforwardly demonstrate that even in the nearby universe there is much material which is not associated with any catalogued galaxies. Attempts to associate the redshifts of these QSO absorption line systems with known galaxies have so far proved negative (Salzer 1 992; van Gorkom et al. 1993), although there now is some evidence for ionized Hydrogen at the redshift of one of these absorption line features (see Williams and Schommer 1994). Hence there is ample circumstantial evidence, as well as sensible physical theory (e. g., Wyse and Gilmore 1 992) that galactic winds in ubiquitous low mass galaxies can move cold gas from these local sights to a more large scale, lower column density, distribution. This conjecture can now be directly tested by searching for extended, soft, X-ray halos around low mass disk galaxies.

2.2 Choice of Sample

In constructing a sample of low mass disk galaxies to be observed with ROSAT we used the following selection criteria: 1) A velocity dispersion, as judged by the width of the 21-cm HI line, of 100 200 km s^{-1}, 2) blue colors indicative of a recent star-formation event, 3) low fractional H 1 contents perhaps indicative of the loss of cold gas due to the recent star formation event 4) distances less than 25 Mpc to ease detection and 5) few or no 1 1 H regions indicative of little or no current star formation. An actively star forming system would be expected to have a strong contribution of Population I sources (Ills.ssive X-ray binaries, supernova remnants) to the total X-ray flux.

Lists of low-mass disk galaxies, such as those found in Bothun et al. (1 989a) or Schombert et al. (1 992) win-c consulted in order to form a sample. Ideally, the sample Should contain a range of disk surface brightnesses as this might correspond to a range of post-burst timescales. Using the criteria listed above, we identified five suitable candidates which are listed, along with some of their characteristics, in Table 1. In table 1, column 1 gives the galaxy ID and column 2 lists its observed velocity, obtained from 21-cm observations. Column 3 lists the observed velocity width of the 21-cm line at the 50% peak intensity level. This provides some measure of the depth of the potential of the galaxy and is roughly equivalent to a velocity dispersion. Columns 4-7 list the foreground galactic column density towards the galaxy, the observed H I mass, and, when measured, the integrated B-I color and ratio of Far Infrared to Blue luminosity. Unfortunately, only three of these targets were actually observed by ROSAT.

CCD images of these three targets are shown in Figure 1 and a brief description is given below. The optical data was obtained with the MDM 2.4-m telescope on 29 Apr 1993 using the Wilbur imaging system at Cassegrain. Wilbur is a thick, front-side illuminated Loral 2048x2048 CCD with 15 μ pixels. The chip was rebinned 3 by 3 for a plate scale of 0.51 arcsec per pixel. Data was taken for 200 secs in Johnson B, V and I. Twilight flats were used to flatten the B and V data while sky flats were used for I. Calibration was performed with 15 standards from the lists of Landolt (1992).

NGC 5089: This is a moderately strong emission line galaxy which was originally detected by Wasilewski (1983). Its disk appears to be disturbed but the luminosity profile is quite regular (see Bothun et al. 1989a). The inner 0.5 kpc exhibits a noticeable excess of light relative to the extrapolated exponential. This galaxy was detected by IRAS and has a 60/100 μ flux ratio of 0,92 which is quite high (see Bothun et al. 1989b, Mazzarella et al. 1991) and is indicative of dust which is heated by OB stars or, more likely, an AGN. The disk colors are fairly blue as well. Thus it seems likely that NGC 5089 had a "nuclear" starburst which is now dying out, judging from the emission line strength.

1C2520: This is an irregular galaxy which is at the distance of the Virgo supercluster. It also appears in the emission line galaxy sample of Wasilewski (1 983) with a weaker line strength than NGC 5089. The IR AS detected 60/100 μ flux ratio is 0.56, again indicative of dust heating by some OB stars. The surface brightness profile is well fit by an exponential and their is no nuclear excess of light (see Bothun et al. 1989a).

1C3522: This is a well-st,udicd dwarf irregular galaxy which is a member of the Virgo supercluster. A detailed H 1 map is given in Skill man et al. (1987) and the relevant optical surface photometry can be found in Bothu n et al.(1986). This galaxy is one of a handful of low surface brightness (LSB) low mass galaxies which have been detected in H 1 in Virgo. There are no obvious signs of H 11 regions or current star format ion in this galaxy even though its continuum colors are rather blue (e.g., B - V = 0.46). Of the five galaxies in our sample, this one comes closest to meeting all the selection criteria in the most favorable terms. This galaxy was not detected by I]{ AS.

2.3 Expected Signal Strength

To estimate the signal strength from a hypothetical halo of warm tenuous gas we must make plausible assumptions about its gas mass, physical extent and temperature. The typical H 1 mass of our sample galaxies 5 x 108 $M_\odot$. With these observations, we are interested in detecting galaxies where the majority of the gas mass is in a hot, rarified plasma instead of a cold dense medium. This is the situation for elliptical galaxies. We hence adopt a gas mass of $10^{10} M_\odot$ which is distributed in a uniform density sphere of radius 20 kpc (the optical radius of a typical galaxy in our sample is 5 kpc). This adopted gas mass is approximately equal to the stellar mass of the target galaxies.

To fix the temperature, we further assume an internal velocity dispersion, of 150 km s^{-1}

andno metals. These parameters yield an electron density, N_e of 0,017 cm^{-3} and a Bremsstrahlung cooling rate of 6 x 1041 ergs s^{-1}. The total luminosity in the ROSAT PSPC bandpass (0.1 2.4 keV) is then 1.8x104] ergs s^{-1}. Assuming a galactic column density towards these sources of 3 x 1 0^{20} (111 $^{-2}$ and an ECF of 0.33 x 10^{11} cts cm^2 erg^{-1} yields a total count rate on the PSPC detector of 0.12 counts per second which corresponds to an unabsorbed flux of 3.8 x10^{-12} ergs^{-2}cm^{-1} Hence, exposure times of a few thousand seconds will easily detect our hypothesized configuration of halo gas. Moreover, the angular size of this hypothesized halo would be (i 10 ', which is well resolved by the PSPC. Finally, the derived cooling time for this halo is 4 x 10^8 years (somewhat short because of the high N_e) which is much longer than the duration of the starburst, and hence, any gas ejected by the energetics of the most recent star formation event, should remain hot for son ıe time after the starburst has faded. This is why we have tried to pick a range of disk surface brightnesses and emission line strengths in our sample. These model calculations are quite encouraging as they indicate that if such extended balm exist, then ROSAT PSPC observations should be able to detect them.

3 Results

Of the original five targets proposed for observation by R OS A'J', onl y the first four were accepted. of those, data were obtained for three objects; NGC 5089 with a total exposure time of 7786 secs, IC 2520 for 6755 secs, and IC 3522 for 1264 secs. With these exposure times only NGC 5089 and IC2520 were detected. Co n tour plots of the total band emission, as w c]] as emission in the soft and hard bands, are shown in Figures 2a-i. The contours begin at approximately I σ above the background noise. In each case, the target is located at the field center. Coordinates are epoch 2000.0 equatorial. For completeness, we also include the limited data on IC3522 even though it was not detected. Table 2 contains a list of identifiable extragalactic counterparts to the detected sources in each field. Columns 1-3 give the extragalactic ID (as obtained using NED) and the epoch 2000 coordinates. The remaining columns list the measured net source counts, the observed flux and whether or not the source is resolved. We now discuss each of these fields.

NGC 5089: This galaxy is weakly detected in total band emission but completely absent in the soft X-ray band. In the hard band, the galaxy is easily detected and is clearly unresolved. Since this galaxy is the most actively star forming, it is most likely that we are seeing X-ray emission from the nuclear star burst and/or AGN. At our assigned distance, the total X-ray luminosity, corrected for foreground absorption, is 2.4×10^{39} ergs sec^{-1}, far below the expected luminosity if the gas were distributed in a halo. The blue band luminosity of NGC 5089 is approximately 2.5×10^{9} $L_{\odot}$ (see Bothun et al. 1989a). The X-ray /optical correlation for spirals reported in Fabbiano et al. (1992) would then predict an *0.2- 4.0* kev luminosity of 0.5×10^{39} ergs sec^{-1}. Thus NGC 5089 has an elevated level of X-ray emission which is most likely associated with its starburst nucleus. There is no evidence for any diffuse halo around this low mass galaxy. The approximate size of such a halo corresponds to one grid element in Figure 2.

We also note in this field, a pair of sources with respective fluxes of 2.56 and 2.54×10^{-13} ergs cm^{-2} sec^{-1}. These are the pair of sources at approximate position $13^h20^m15^s$ and +30°05'. A cross-correlation with the HST Guide Star Catalog produced no positional coincidences. Inspection of the Palomar Sky Survey reveals a pair of unresolved, ≈ 18th magnitude objects which are the likely optical counterparts. Their image diameters are very similar between the Blue and Red prints indicating they are of similar color and neither very red or blue. Follow-up spectroscopy is desirable, although it seems likely that will turn out to be galactic stars.

IC2520: At the field center there are two sources that could be identified with the target galaxy but the overall source extent is much less than the expected size of an extended halo. The brightest source of the 2 is dominated by emission in the hard band and may well be a background source. Its positional centroid is ~ 1 arcminute to the north of the position of IC2520. IC2520 proper, appears to be very weakly detected in the soft X-ray band, again as an unresolved object. The total X-ray luminosity associated with the apparently multiple sources at the position of IC2520 is 1.45 x 10^{39} ergs sec^{-1}, or a factor of 2 lower than the case of NGC 5089. However, the Blue-band luminosity of IC2520 is down by a factor 4 and thus, apparently IC2520 is an order of magnitude more over luminous in the X-ray band relative to what would be expected from the optical luminosity. We take this as a very likely indication that indeed, IC2520 is contaminated by a background source. Once again, there is no evidence of any extended, diffuse soft-x ray emission which could plausibly be associated with a halo.

IC3522: The limited exposure time available for this field did not allow for a detection of the galaxy and the data are not sensitive enough to have detected any halo, had it been present at the predicted level. What is of interest in this field, however, is the complex set of contours which appear to be made up of multiple sources, one of which is the likely serendipitous detection of the background cluster Abell 1560. Abell 1560 appears to be the middle of the three sources which al] have overlapping contours. The other two sources call be identified with NGC *4523 (SW* of Abell 1560) and the radio source discovered in the GB87 survey of Gregory and Condon (1991) (NE of Abell 1560). Note that the radio position of the radio source is not coincident with the x-ray contours but rather is Offset about one arcminute to the cast, where the contours have their steepest gradient. This is similar to the standard head/tail morphology seen for radio sources in some clusters and may suggest that this source is actually in the Abell 1560 cluster.

Abell 1560 is a distance class 7 cluster which currently is at unknown redshift. Figure 3 shows the spectrum obtained from the PSPC data. Although the count rate is low, a reasonable fit to the spectrum can be made using a thermal Bremsstrahlung model with a temperature of 2.2 Kev. The observed flux is 2.45 x 10^{-13} ergs cm^{-2} sec^{-1}, which is below the sensitivity of the ROSAT all sky survey. If this cluster is located at $z = 0.4$, its luminosity would be approximately 10^{43} ergs see-'. Follow-up spectroscopy to determine the redshift of this cluster is clearly desirable.

4 Summary Discussion

The primary goal of these particular ROSAT AO observations was to detect soft X-ray halos around low mass disk galaxies that serve as repositories for gas which was expelled from the galaxy during; its most recent episode of star formation. Since rather long exposure times are required for the detection of any halo with plausible physical properties, only deep pointed observations will reveal their presence, if indeed they exist. Unfortunately, 110 such halos were detected for our t] rec t argets. The observed luminosities arc two orders of magnitude less than the case in which the gas mass in the halo is *approximately* equal to the stellar mass in the galaxy, Thus, if an extended halo really is present, its total gas mass is much less than current cold gas content in these systems. Thus, we are unable to verify the hypothesis, for these three galaxies, that galactic winds associated with star formation serve to relocate most of the cold disk gas to a warm tenuous halo. Alternatively, our non-detection could mean that these galaxies do not possess a sufficiently massive halo to aid in the retention of this gas,

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